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AN INVESTIGATION OF THE EFFECT OF THE HUB MOTOR WEIGHT ON VEHICLE SUSPENSION AND PASSENGER COMFORT

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ABSTRACT

One of the most critical components in a vehicle is the suspension system, as it is responsible for stability and handling in the vehicle structure and thus ensuring the passenger's comfort because it absorbs shocks caused by different road conditions and prevents them from reaching the passengers' seats. A passive suspension system with eight degrees of freedom was investigated and evaluated in two cases in this research: the first case using standard wheels the second case using hub motors. To complete this work, the equations of motion of the suspension system were shown then the full model construction was implemented using Matlab. It is known that the hub motor weight is bigger than the standard wheel weight that's why this work obtain a little bad effect on vehicle performance when using hub motors, an active suspension system that can improve vehicle performance and ride comfort is recommended.

KEYWORDS: Suspension System, Hub Motor, Vehicle & Ride Comfort

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NOMENCLATURE

W1, W2, W3, W4	The wheel hub motor weight in Kg
W	The sprung weight is expressed in Kg
Wp	The weight of the passenger seat in Kg
S1, S2, S3, S4	The spring stiffness in N/m on each side
b1, b2, b3,b4	The damper coefficient in N.s/m on each side
A	The vehicle's half-width in m
B, C	Location of the C.G. from the front and back axles, respectively in m
St	The wheel stiffness is measured in N/m
Kp	Stiffness (N/m) of the passenger seat
bp	The damping coefficient of the passenger seat (in Ns/m)
Xp, Zp	Seat location with relation to the sprung mass's centre of gravity (m)

θ	Displacement of the sprung mass pitch in radian
∅	The radian displacement of the sprung mass roll
Q1, Q2, Q3, Q4	Each side's actuator force in N
Y1, Y2, Y3, Y4	The profile of the road (road input) at each wheel in m
Y11, Y22, Y33, Y44	The displacement of the wheel on each side in m
Ix	Rolling mass moment of inertia in (kg-m^2)
Iz	Roll's mass moment of inertia in (kg-m2)

1. INTRODUCTION

When you consider your vehicle's performance, you typically focus on its horsepower, torque, and acceleration, overlooking more significant factors. Specialists, the most critical of which is the suspension system of the car. Following the development of the four-stroke internal combustion engine, engineers focused on the vehicle's suspension system, which is responsible for maximizing the friction between the car's wheels and the road surface. This is to ensure the car's stability when driving, particularly on difficult roads, and to ensure the comfort of passengers inside the vehicle. Suspension systems are not required if the road is fully flat and without bumps, although this is rarely the case, and it is worth mentioning that the road does contain certain flaws. It will undoubtedly have an effect on your vehicle's wheels (1).

The purpose of this article is to construct and analyse a simple suspension vehicle model that can be used for simulation in the Matlab Simulink environment. Numerous contributions analyse simply the whole passive suspension model and then use it for analysis, synthesis, and finally for stability and ride comfort validation via simulations. While our model is not explicitly specified here for the control and synthesis problems, the use of a comprehensive vehicle suspension model with a passenger is critical for simulation in a wide variety of vehicle sectors and applications.

One of the suspension system's objectives is to isolate the vehicle's body from road disturbances in order to provide a comfortable ride, while the other functions include ensuring good road holding, giving appropriate handling, and supporting the vehicle's static weight (2).

In today's suspensions, hydraulic dampers (alternatively referred to as shock absorbers) and springs are used to absorb bumps, limit body motions of the vehicle during acceleration, braking, and turning, and keep tires in contact with the road surface. These goals often contradict each other. Luxury vehicles are great for absorbing bumps and delivering comfortable driving, but handling has a tendency to pitch and dive in acceleration and braking, and to be lean on the body (or "sway") think Town of Lincoln (3).

Multi-body dynamics have long been used by the automotive industry to design and refine suspension. In order to test iteratively multiple input factors for car suspension performance before the adoption of new optimisation approaches. Till the present performance targets were fulfilled, the analysis will be carried out. Optimization of the design, parametric tests and sensitivity analysis were challenging, if not impossible. This traditional optimization approach, generally followed by prototype testing, can be difficult and time-consuming for completely sophisticated systems. With the

introduction of numerous optimization methods and advancing computer technology, the design process has been accelerated to achieve optimal values and studies on the influence of design aspects to acquire the minimum/maximum of an objective function subject to limits. These restrictions incorporate practical considerations into the design process (4).

A key concern arose with the arrival of hub engines in the field of electric vehicles: 'What does the additional wheel weight of a hub engine affect the safety and comfort of a car. The unsprung mass of moving power from the motor carrier to the wheels might be as large as 50 kg or more per rolling wheel. Most suspension research in conventional cars has been carried out(5). There was no serious analysis of the increased mass. The unsprung mass should not exceed 20% of sprung mass according to several recommendations (6),in the existing road vehicle fleet, this ratio is not exceeded, and there is no solid evidence to support it.

The impact of wheel hub motors on vehicle ride comfort was tested on the highway with the VW Lupo 3L. The experimental results are used in validating the SimMechanics software model of a comprehensive automobile simulation. It is intended to examine the impact of hub motors on the comfort and road maintenance of a battery-electric car. It was also used to investigate possible improvements to ride comfort and road holding by optimizing suspension systems or using an electromagnetic suspension system controlled by a skyhook control or a hybrid control technique (7).

Note: This study is an extension of a study conducted on the same topic in reference number (17).

2. WHEEL HUB MOTOR TECHNOLOGY

The wheel hub motor (also known as an in-wheel motor, wheel motor, or hub motor) is an electric motor that is built into a wheel's hub and drives it directly.

Because there have been numerous studies on the interest in the use of a hub motor drive system as electric automobiles. Related items started appearing on the market. A hub wheel motor drive system that places or develops engines adjacent to the wheel can also be used for various conveys, such as electric bicycles, two-wheeled electric motor chairs and four-wheeled electric vehicles (8-9).

The primary components of the wheel hub motor and the unsprung assembly, which were both built by Protean Electric, are depicted in figures 1 and 2, respectively. Protean Electric is an automotive technology innovator and a world-leading developer of hub motors and future propulsion systems. Protean Electric is headquartered in the United Kingdom. Protean Electric, which was established in 2008, has invested more than one million engineering person-hours in the development and validation of their Protean Drive wheel hub motor technology.

Figure 1: Wheel Hub Motor Components.

Figure 2: Front-Left Corner of a Protean/Brabus E-Class (Unsprung Assembly).

3. SYSTEM AND MATHEMATICAL MODEL

A whole vehicle model with eight degrees of freedom is analyzed for the purposes of analysis and evaluation. Figure 3 displays a full vehicle suspension model, which includes the passenger seat, sprung mass (the component of the car supported by springs), and unsprung mass (the component of the car that is not supported by springs) (the mass of the wheel assembly). Wheel stiffness has been substituted with its equivalence, and wheel damping has been completely omitted in this calculation. To simulate the suspension, wheel, and passenger seat, linear springs in parallel with dampers are used in conjunction with dampers. The sprung mass has three degrees of freedom (bounce, pitch, and roll) in the vehicle model, but the passenger seat and four unsprung masses each have 1 DOF in the vehicle model.

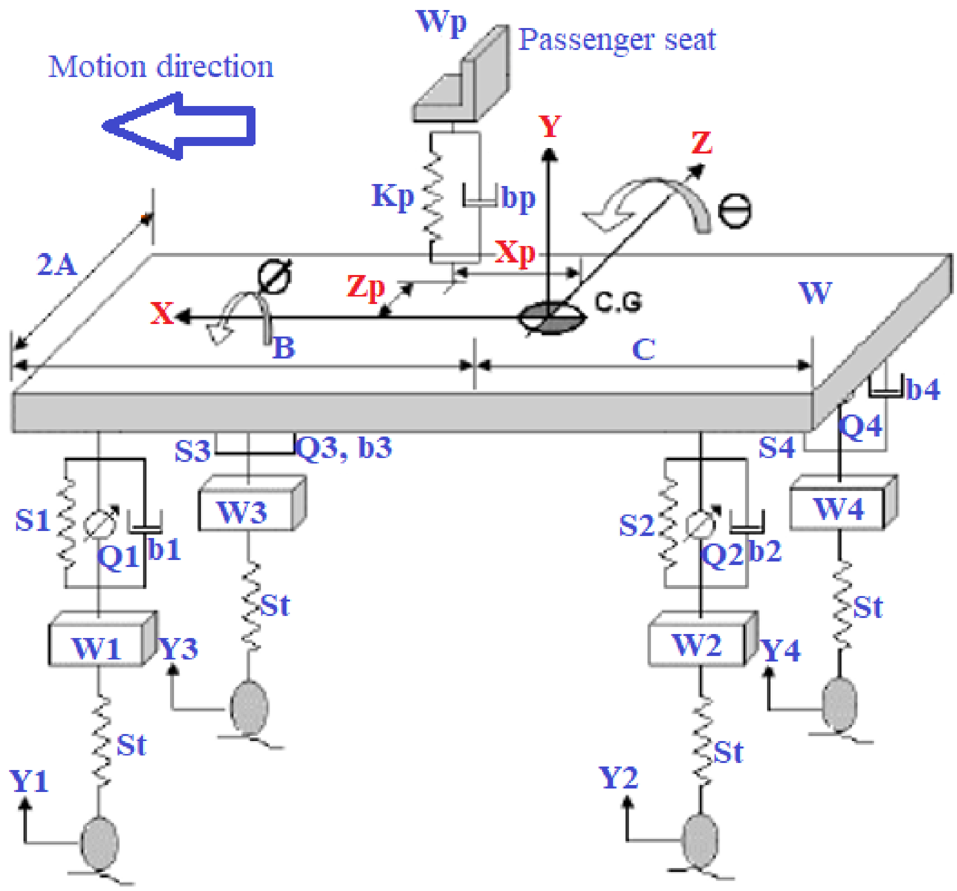

Figure 3: Full Vehicle Suspension Model.

W1andW3 is both left-side and left-front unsprung mass, whereas W2 & W4 respectively rear left-hand and right-hand unsprung masses these four unleash masses are employed as standard wheels, and in other times as hub wheel motors. In this paper, these four unsprung masses are used. Table 1 and Table 2 show the specifications of the wheel hub motors for both front and rear wheels.

Table 1: The Motor Specs Utilized at the Unsprung Mass on the front Left and Right Sides, Respectively.

Company and Hub Motor Type	**ELAPHE LTD. (S400)**
Additional weight	17.5 kg
Maximum torque	400 Nm
Maximum power	45 KW
Top speed	1570 rpm
Continuous power (liquid cooling)	25 kW

Table 2: The Motor Specs Utilized in the Rear Left and Rear Right Unsprung Masses, Respectively.

Company and Hub Motor Type	ELAPHE LTD. (M70)
Additional weight	25 kg
Maximum torque	More than 700 Nm
Maximum power	79KW
Top speed	1665 rpm
Continuous power (liquid cooling)	52 kW (liquid cooling)

Based on Newton's second law of motion, the equations of motion for the system represented in figure 3 can be stated as follows:

$$W\ddot{Y} + S1(Y - B\theta + A\emptyset - Y1) - Ab1(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}1) + AS2(Y + C\theta + A\emptyset - Y2) + Ab2(\dot{Y} + C\dot{\theta} + A\dot{\emptyset} - \dot{Y}2) - AS3(Y - B\theta - A\emptyset - Y3) - Ab3(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}3) - AS4(Y + C\theta - A\emptyset - Y4) - Ab4(Y + C\dot{\theta} - A\dot{\emptyset} - \dot{Y}4) + ZpKp(Yp - Y - Xp\theta - Zp\emptyset) + Zpbp(\dot{Y}p - \dot{Z}Y - Xp\dot{\theta} - Zp\dot{\emptyset}) - AQ1 - AQ2 + AQ3 + AQ4 = 0$$
(1)

$$Ix\ddot{\emptyset} + AS1(Y - B\theta + A\emptyset - Y1) - b1(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}1) + S2(Y + C\theta + A\emptyset - Y2) + b2(\dot{Y} + C\dot{\theta} + A\dot{\emptyset} - \dot{Y}2) + S3(Y - B\theta - A\emptyset - Y3) + b3(\dot{Y} - aB + A\dot{\emptyset} - \dot{Y}3) + S4(Y + C\theta - A\emptyset - Y4) + b4(\dot{Y} + C\dot{\theta} - A\dot{\emptyset} - \dot{Y}4) - Kp(Yp - Y - Xp\theta - Zp\emptyset) - bp(\dot{Y}p - \dot{Y} - Xp\dot{\theta} - ZYp\dot{\emptyset}) - Q1 - Q2 + Q3 + Q4 = 0 \quad \textbf{(2)}$$

$$W\ddot{Y} + Kp(Yp - Y - Xp\theta - Zp\emptyset) + bp(\dot{Y}p - \dot{Y} - Xp\dot{\theta} - Zp\dot{\emptyset}) = 0 \quad \textbf{(3)}$$

$$Iz\ddot{\theta} + BS1(Y - B\theta + A\emptyset - Y1) - Bb1(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}1) + CS2(Y + C\theta + A\emptyset - Y2) + Cb2(\dot{Y} + bC + A\dot{\emptyset} - \dot{Y}2) + BS3(Y - B\theta - A\emptyset - Y3) + Bb3(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}3) + CS4(Y + C\theta - A\emptyset - Y4) + Cb4(\dot{Y} + bC - A\dot{\emptyset} - \dot{Y}4) + XpKp(Yp - Y - Xp\theta - Zp\emptyset) + Xpbp(\dot{Y}p - \dot{Y} - Xp\dot{\theta} - Zp\dot{\emptyset}) + BQ1 - CQ2 + BQ3 - CQ4 = 0$$
(4)

$$W1\ddot{Y}11 - S1(Y - B\theta + A\emptyset - Y11) - b1(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}11) + St(Y11 - Y1) + Q1 = 0 \quad \textbf{(5)}$$

$$W2\ddot{Y}22 - S2(Y + C\theta + A\emptyset - Y22) - b2(\dot{Y} + C\dot{\theta} + A\dot{\emptyset} - \dot{Y}22) + St(Y22 - Y2) + Q2 = 0 \quad \textbf{(6)}$$

$$W3\ddot{Y}33 - S3(Y - B\theta - A\emptyset - Y33) - b3(\dot{Y} - B\dot{\theta} + A\dot{\emptyset} - \dot{Y}33) + St(Y33 - Y3) + Q3 = 0 \quad \textbf{(7)}$$

$$W4\ddot{Y}44 - SK4(Y + C\theta - A\emptyset - Y33) - b4(\dot{Y} + C\dot{\theta} - A\dot{\emptyset} - \dot{Y}44) + St(Y44 - Y4) + Q4 = 0 \quad \textbf{(8)}$$

4. ROAD PROFILE (Y1, Y2, Y3, and Y4)

As illustrated in figure 4, the road bump at each wheel assumed a single profile in this study, and the subsystem Simulink model of the input bump road *Yi* was created.

Figure 5 depicts a single bump road input (*Yi*) that is used to express the road state and conditions, as well as to verify the created system. This road bump is referred to as a road profile or a road disturbance, and it is set to reach a bump height of 0.05 m.

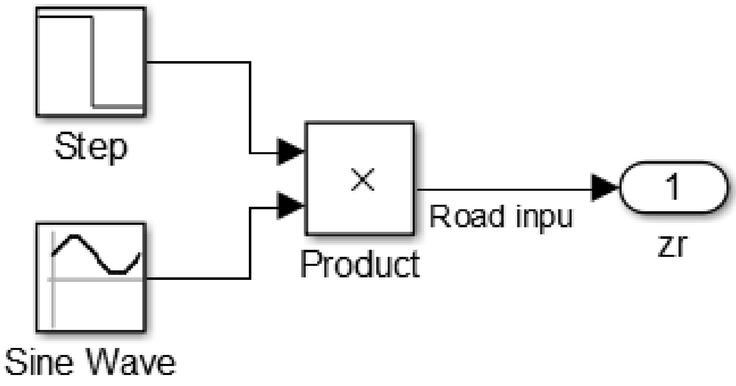

Figure 4: Subsystem Model of the Bumpy Road Input.

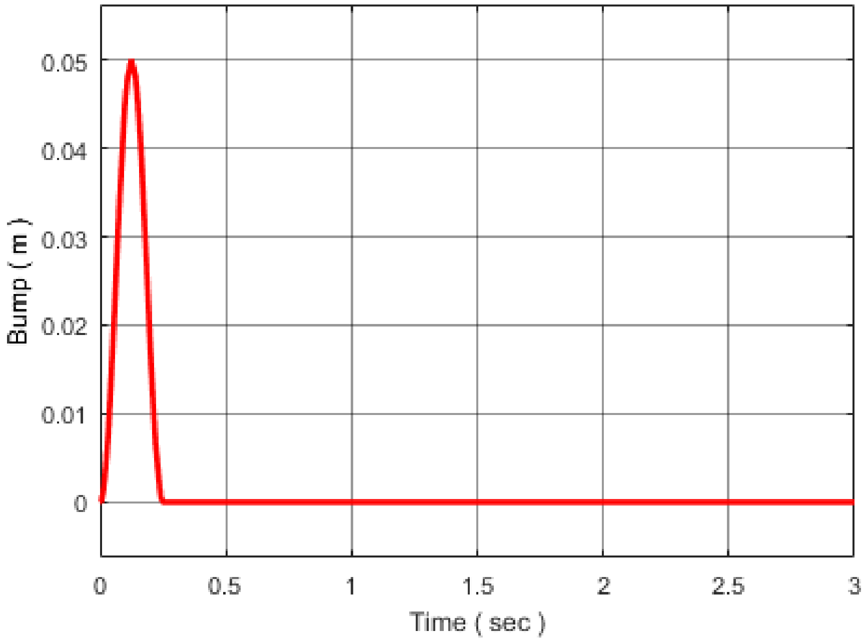

Figure 5: Bumpy Road Input Signal at Each Wheel.

The Matlab/Simulink software was used to create the Simulink model of the Suspension System shown in figure 6, which was implemented according to the free-body diagram of the full vehicle suspension system in figure 3 and the eight equations of motion mentioned above, as well as taking into account bumpy road input signals at each wheel.

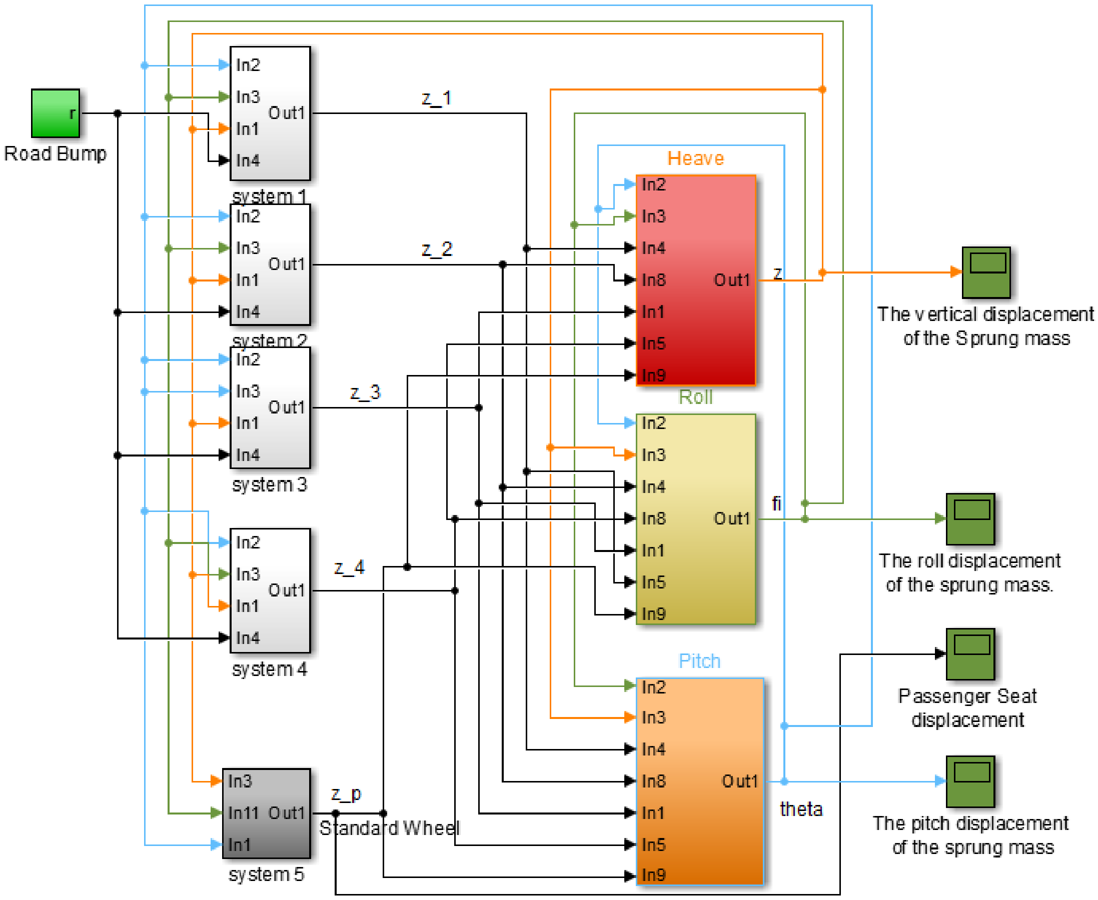

Figure 6: Full Representation of the Suspension System in Simulink.

5. SIMULATION RESULTS AND DISCUSSIONS

The proposed scheme for suspension system has been simulated using MATLAB/SIMULINK under certain condition and parameters. Figure 3 shows the full suspension system used in this paper that has been used in the simulation, where Y1, Y2, Y3 and Y4 are the vertical displacement of road at each wheel, whileW1and W3 are Front left and front right side wheel weightin kilograms respectively, while W2 & W4 are Rear left and rear right side wheel weightin kilograms respectively. The output response has been simulated for change in road profile of 0.05m.

As previously stated in this work, the purpose of this investigation is to analyse the performance of the vehicle in two scenarios, the first case is the use of four standard wheels, while in the second case four wheel hub motors were used.

The outputs of the model system depicted in Figure 6 are four major output metrics that clearly demonstrate the vehicle's performance, which is clearly relevant to ride comfort and road handling. The vertical displacement of the sprung mass, the roll displacement of the sprung mass, the displacement of the Passenger Seat, and the pitch displacement of the sprung mass are the four components that give an indication of the vehicle performance.

Figures 7-10 show the selected four output parameters of the system, all figures showed that the vehicle performance was better duringthe use of standard wheels compared to the wheel hub motors, which means that the use of the in-wheels had a negative impact in a simple way, especially in Figure 9 which shows the sprung mass roll

displacement. The reason for the negative impact on the performance of the studied suspension system in the case of using hub motors is the increase in the mass of these wheels, which has led to a decrease in passenger comfort and road handling.

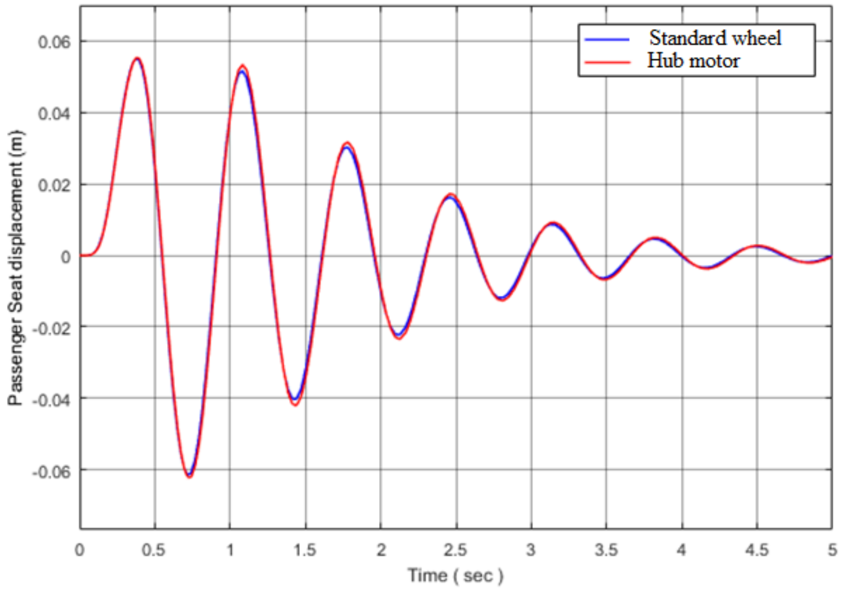

Figure 7: Passenger Seat Displacement.

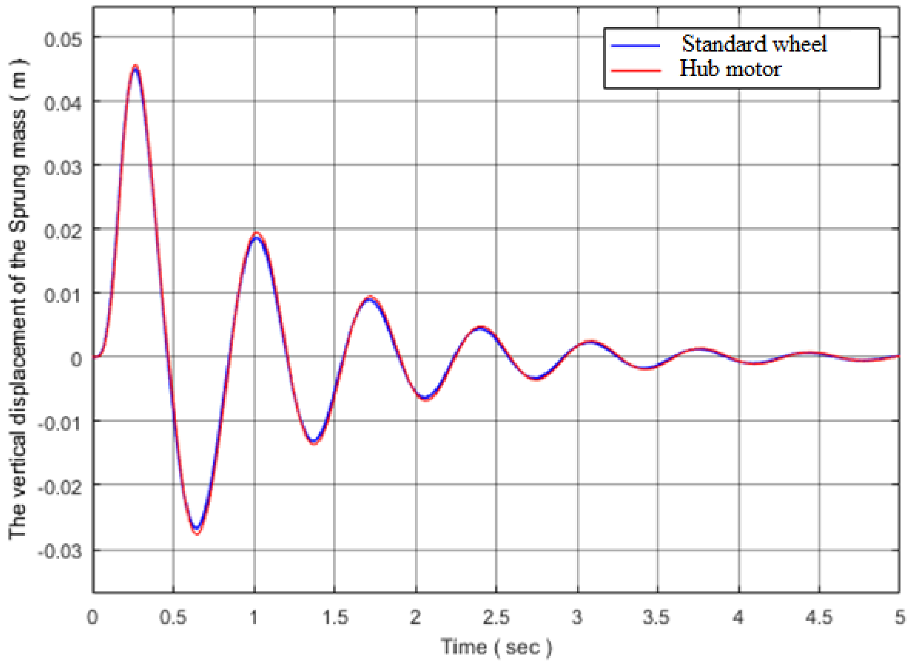

Figure 8: The Sprung Mass's Vertical Displacement.

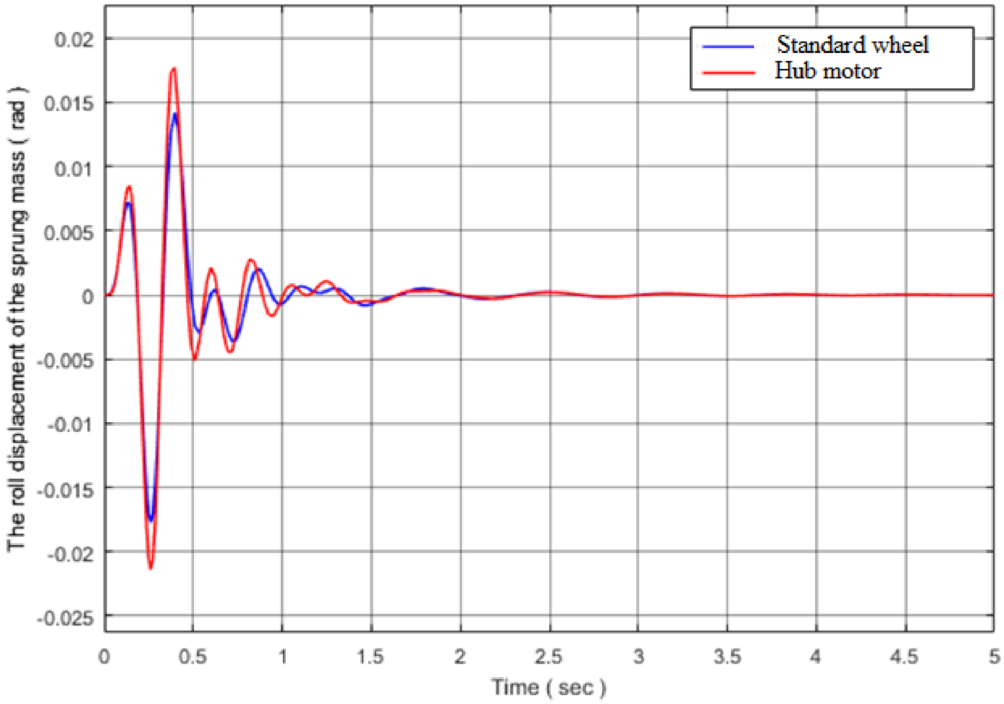

Figure 9: The Sprung Mass's Roll Displacement.

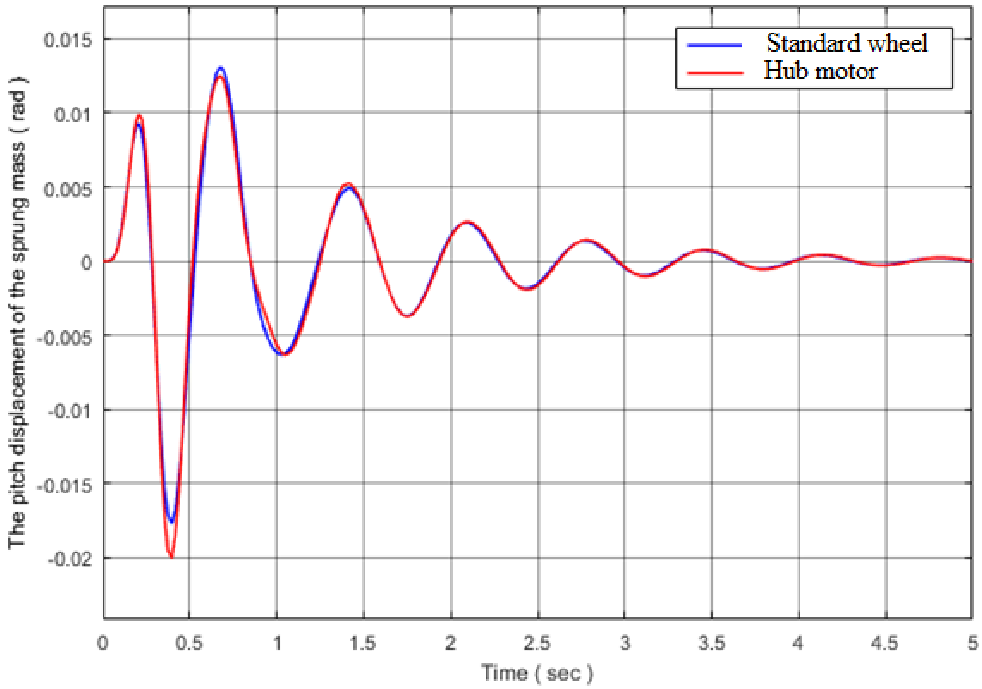

Figure 10: The Sprung Mass's Pitch Displacement.

6. CONCLUSIONS

In this paper, a performance of full vehicle suspension system is evaluated, where the system was studied evaluated in two cases, the first case when using standard wheels for the vehicle, while the second case when using wheelhub motors. Standard wheels provide a positive effect on suspension system performance over purely wheel hub motors. Based on the

simulation results, it is obvious that increasing the amount of sprung mass has a negative effect, particularly in the pitch and roll displacements of the sprung mass.

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